BEAST Simulator Manual

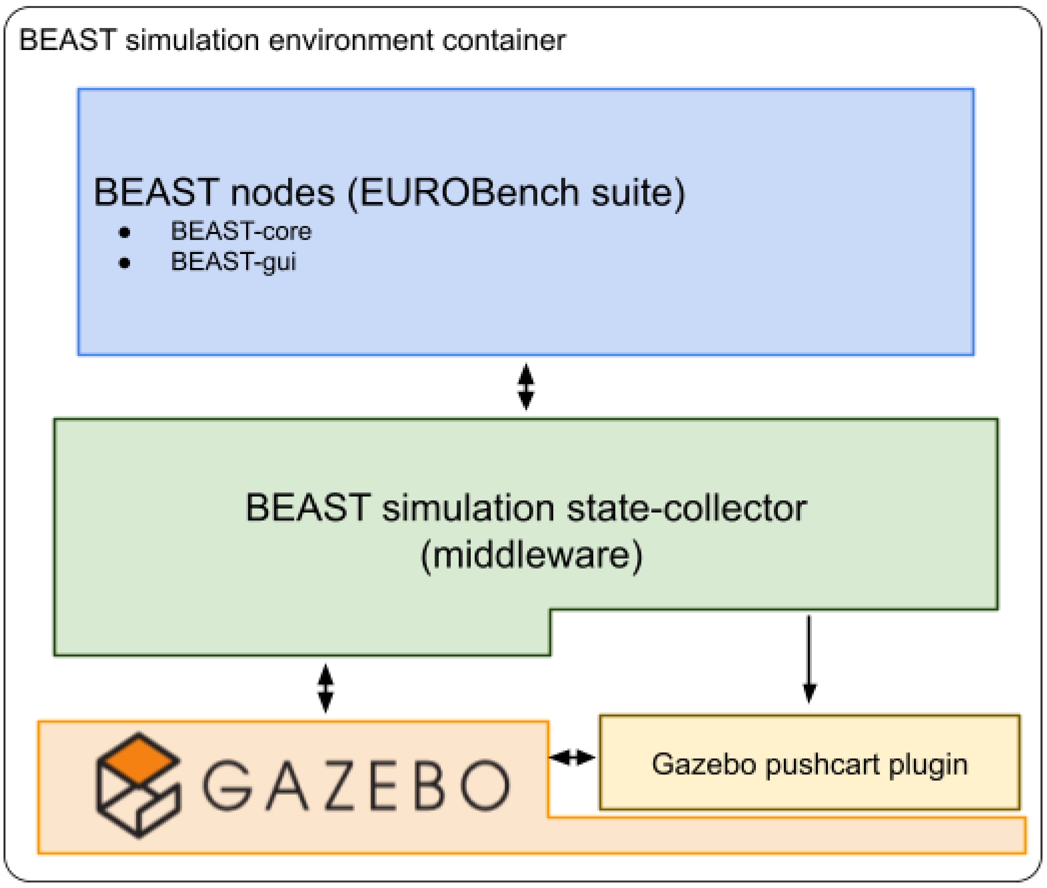
Simulation environments are a fundamental tool to boost the research and the development of new methodologies and approaches within the robotics and AI community. In fact, having the possibility to gain access to a reliable simulation software that resembles a target task, and environment, allows researchers to explore a wide range of solutions and to remarkably reduce time and cost in the development process. The BEAST EuroBench project provides such a critical instrument. To this end, this manual provides a thorough overview of the EuroBench BEAST simulation suite: how to install, the overall architecture and how to run the simulation.

Manual

eurobench
European robotic framework for bipedal locomotion benchmarking

Architecture

Before diving in the simulator features and installation guide, let us understand the overall architecture, its building blocks and data exchanged among different components. The figure below summarizes the architecture of the BEAST simulation environment.


BEAST simulation environment container
BEAST nodes (EUROBench suite)
BEAST-core
BEAST-gui
BEAST simulation state-collector (middleware)
GAZEBO
Gazebo pushcart plugin

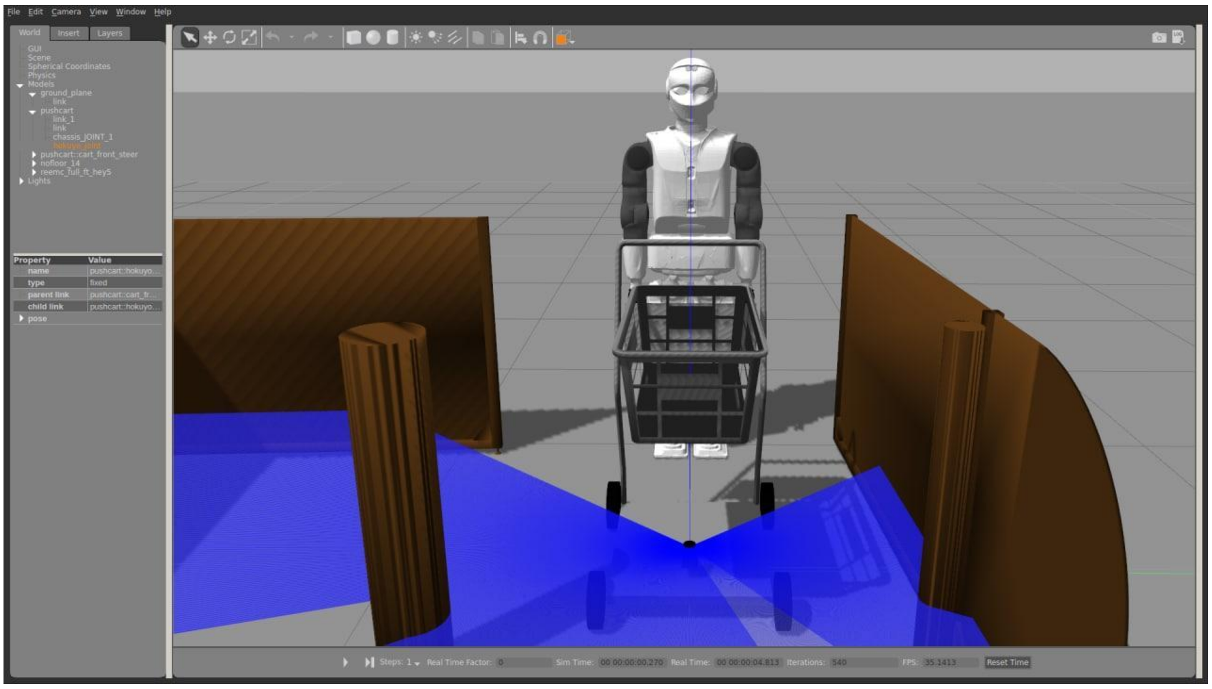
Gazebo Pushcart Plugin

The gazebo pushcart plugin contains the core computation routines to update the simulated pushcart parameters and it exploits the ros-transport class to access ROS-nodes from an external source (http://gazebosim.org/tutorials?tut=guided_i6). Upon startup, the plugin receives all the initialization values needed to configure a particular run of the benchmark.
The plugin is in charge of (1) assessing that all the ROS-nodes needed for the benchmark are operational; (2) read the laser scan sensor readings and pushcart handle contact forces; and (3) to load the pushcart wheels LookUpTable (LUT) containing the force torques to be applied to the wheels during the benchmark at run time.
Then, at each cycle of the simulation, it listens to the BEAST simulation middleware and waits for changes in the benchmark parameters such as the force torques LUT.
The pushcart plugin communicates with both the Gazebo simulator and the BEAST simulation middleware. The former communication executes a constant and cyclic

supervision of the pushcart simulation. In particular, the simulator tells the plugin the current location of the pushcart, the plugin computes the force to be applied based on the provided LUT and returns the value to the simulator that sets the force to the wheels (increasing or decreasing friction on the wheels breaks). The latter communication is used instead to configure the benchmark and to wait for parameters changes. The plugin receives a message each time middleware sets a new torque LUT to be updated in a particular benchmark.

BEAST Simulation State-collector Middleware

The middleware module is the core component of the simulation that makes the simulation environment properly configured to run Gazebo, and provides all the available information to the BEAST evaluation suite in a compliant format. It is fundamental in order to achieve effective interchangeability between the real and the simulated robot. In fact, it provides all the information required by BEAST-core and BEAST-gui nodes (https://github.com/madrob-beast/eurobench_benchmarking_software) in the format imposed by the framework allowing the simulated benchmark to be controlled and evaluated via the official BEAST GUI.
The middleware is in charge of configuring and starting the simulation components and receives from the simulator all the sensory information to be passed on to the evaluation suite. In particular, the environment simulates a lidar range sensor placed on the front of the chassis of the pushcart as in figure below. The blue shaded area represents the laser beams. It is worth mentioning that the sensor is a standard lidar range sensor that can be read with the commonly used sensor range topic within the ROS architecture. The name of the topic is /scan.

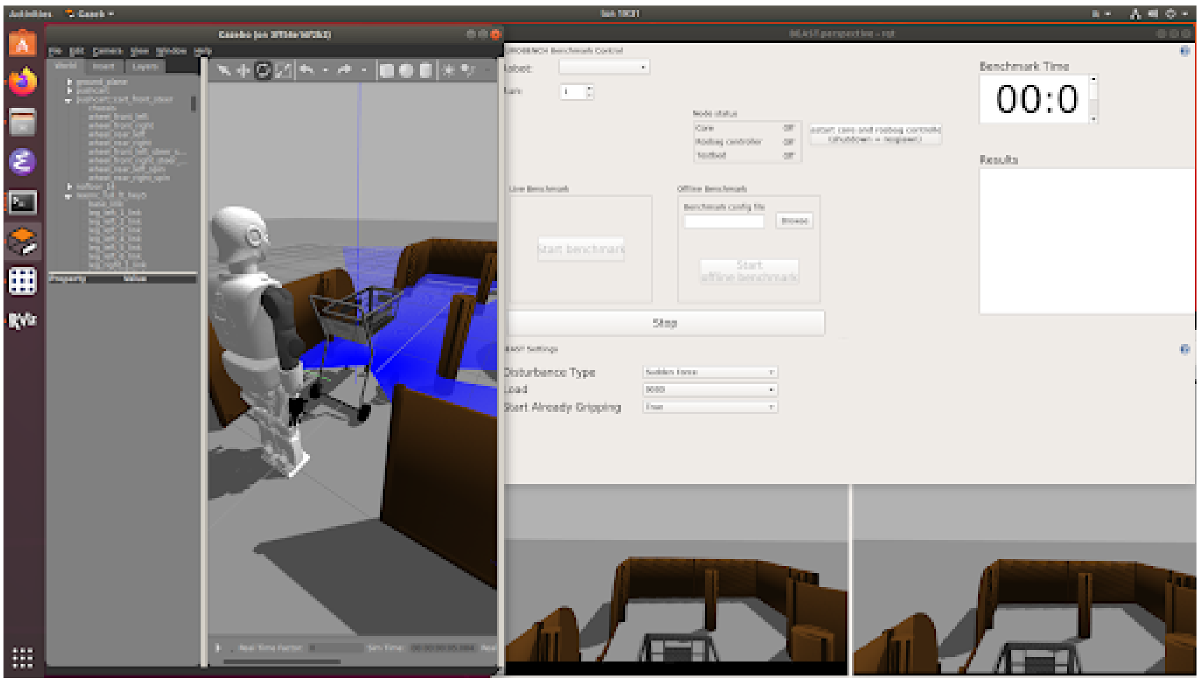


Moreover, along the range sensor readings, middleware receives the pushcart handle contact forces. The pushcart chassis is equipped with two contact forces strips that tell the benchmarking suite the amount of forces applied, by the robot, on both the left and right side of the handle. It is worth mentioning that the force applied to the handle is published on a custom ROS topic message on the topic /beast/handle/force, as specified at https://github.com/madrob-beast/docs/blob/master/beast_performance_indicators_and_preprocessed_data.md.

The simulator also provides the robot camera images retrieved from the robot platform via the Reem-C gazebo plugin. In the bottom-right part, the next figure shows an example of images sampled from the robot camera stream while facing the BEAST challenge. Operationally, the middleware places the robot and the pushcart close together always at the starting position of the benchmark trajectory. Furthemore, the middleware communicates a restart interrupt to the simulator that allows for a quick reconfiguration of the active benchmark.

Communication with BEAST Nodes

The last component in the simulation architecture is represented by the official BEAST framework. On this communication link there is a constant upstream flow of sensory information transferring all the data needed to perform the evaluation of the benchmark in the format required by the evaluation system. The communication link transfers the sensory readings in real time packaging on the proper messages, the laser range scans, the pushcart handle contact forces, the pushcart location and validated trajectory-segment checkpoints, and the robot camera stream. At the same time it communicates downstream to the simulation environment events that require it to restart or to simply update the simulation parameters. As previously introduced, via the BEAST-GUI it is possible to configure the simulated benchmark by setting the wheels force torques LUT. The figures below show the simulation benchmark initialized with the official BEAST-GUI.



Installation

Prerequisite

The BEAST simulator runs in ubuntu and it is configured as a docker container. Such a setup makes the configuration and installation routine pretty straightforward, but on the other hand, introduces hard constraints on the hosting machine. In fact, the simulator can be installed, and it has been tested, on the following ubuntu versions:

- Ubuntu 16.04.7 LTS (Xenial Xerus)
- Ubuntu 18.04.5 LTS (Bionic Beaver)
- Ubuntu 20.04 LTS (Focal Fossa)

The docker container extends the `osrf/ros:kinetic-desktop-full` docker (https://github.com/craymichael/ros-kinetic-nvidia-docker) that contains opengl, glvnd and cuda 8.0. This makes opengl work from any docker environment when used with `nvidia-docker2` (https://github.com/NVIDIA/nvidia-docker). Hence, the simulator can only run on a machine that features an NVIDIA graphic card that supports CUDA with the NVIDIA drivers installed.

Instructions

Install Docker

Docker can be installed by following the instructions in the official website (https://docs.docker.com/engine/install/ubuntu/). In particular, the simulation environment has been built with Docker version 19.03.13. In order to be completely self-contained, here we report the installation instructions that have been used to develop the simulator:

- Update the apt package index and install packages to allow apt to use a repository over HTTPS:

```
$ sudo apt-get update
$ sudo apt-get install apt-transport-https ca-certificates curl gnupg-agent
software-properties-common
```

- Add Docker's official GPG key:

```
$ curl -fsSL https://download.docker.com/linux/ubuntu/gpg | sudo apt-key add -
```

- Verify that you now have the key with the fingerprint 9DC8 5822 9FC7 DD38 854A E2D8 8D81 803C 0EBF CD88, by searching for the last 8 characters of the fingerprint.

```
$ sudo apt-key fingerprint 0EBFCD88
pub   rsa4096 2017-02-22 [SCEA]
      9DC8 5822 9FC7 DD38 854A  E2D8 8D81 803C 0EBF CD88
uid           [ unknown] Docker Release (CE deb) <docker@docker.com>
sub   rsa4096 2017-02-22 [S]
```

- Use the following command to set up the **stable** repository

```
$ sudo add-apt-repository \
   "deb [arch=amd64] https://download.docker.com/linux/ubuntu \
   $(lsb_release -cs)  stable"
```

- Update the apt package index, and install the *latest version* of Docker Engine and containerd, or go to the next step to install a specific version:

```
$ sudo apt-get update
$ sudo apt-get install docker-ce docker-ce-cli containerd.io
```

- Verify that Docker Engine is installed correctly by running the hello-world image

```
$ sudo docker run hello-world
```

This command downloads a test image and runs it in a container. When the container runs, it prints an informational message and exits.

Install nvidia-docker2

The BEAST simulator builds upon the nvidia-docker2 that has to be installed (https://docs.nvidia.com/datacenter/cloud-native/container-toolkit/install-guide.html#docker). Follow the installation instructions:

- Configure the stable repository and the GPG key:

```
$ distribution=$(. /etc/os-release;echo $ID$VERSION_ID) \
   && curl -s -L https://nvidia.github.io/nvidia-docker/gpgkey | sudo apt-key add - \
   && curl -s -L https://nvidia.github.io/nvidia-docker/$distribution/nvidia-docker.list |
sudo tee /etc/apt/sources.list.d/nvidia-docker.list
```

- Update the apt package list and install the nvidia-docker2

```
$ sudo apt-get update
$ sudo apt-get install -y nvidia-docker2
```

- Restart the Docker daemon to complete the installation after setting the default runtime:

```
$ sudo systemctl restart docker
```

- At this point, a working setup can be tested by running a base CUDA container

```
$ sudo docker run --rm --gpus all nvidia/cuda:11.0-base nvidia-smi
```

Clone and Build BEAST Simulator

Now that the docker environment has been properly set up the simulator can be installed pretty easily. The BEAST simulation suite is self-contained in a docker that is also used as a workspace to gather all the BEAST nodes required to run the benchmark. All the setup and configuration is carried out in the Docker file in a way that once completed the docker container provides a link to a working simulation environment. By exploiting the docker paradigm all the step needed in order to install the simulator are to clone the repository and build the docker image with the provided script:

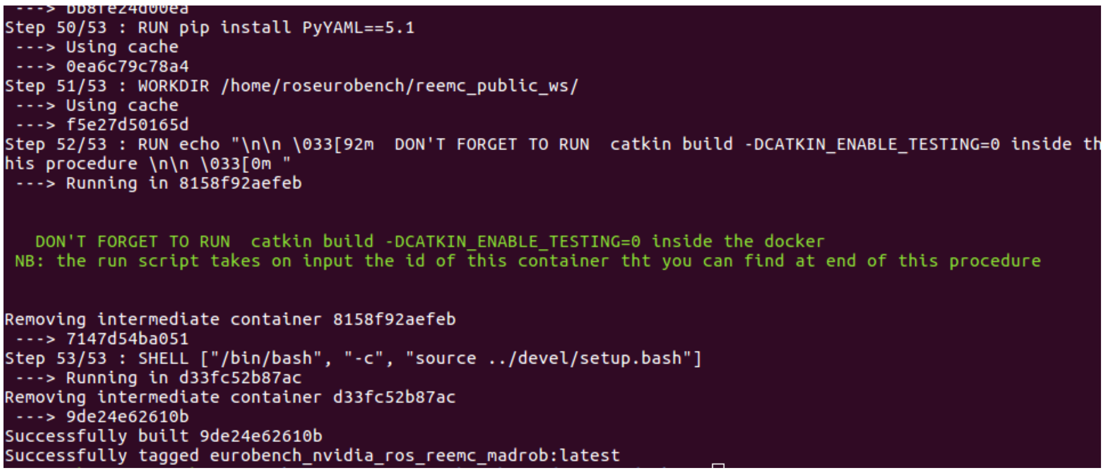
- Clone BEAST simulation repository

```
$ git clone
https://github.com/madrob-beast/eurobench_benchmarking_simulation_software.git
```

- Build the docker image

```
$ sudo ./build_the_container.sh
```

The container downloads and installs all the required components and it takes a few minutes to complete. Upon termination the script outputs the ID of the image (`<ImageID>`) that has to be used to generate the containers. For example, the figure below shows a successful build and the generated imageID is: `9de24e62610b`.



```
 ---> bb8fe24d00ea
Step 50/53 : RUN pip install PyYAML==5.1
 ---> Using cache
 ---> 0ea6c79c78a4
Step 51/53 : WORKDIR /home/roseurobench/reemc_public_ws/
 ---> Using cache
 ---> f5e27d50165d
Step 52/53 : RUN echo "\n\n \033[92m  DON'T FORGET TO RUN  catkin build -DCATKIN_ENABLE_TESTING=0 inside th
his procedure \n\n \033[0m "
 ---> Running in 8158f92aefeb


   DON'T FORGET TO RUN  catkin build -DCATKIN_ENABLE_TESTING=0 inside the docker
 NB: the run script takes on input the id of this container tht you can find at end of this procedure


Removing intermediate container 8158f92aefeb
 ---> 7147d54ba051
Step 53/53 : SHELL ["/bin/bash", "-c", "source ../devel/setup.bash"]
 ---> Running in d33fc52b87ac
Removing intermediate container d33fc52b87ac
 ---> 9de24e62610b
Successfully built 9de24e62610b
Successfully tagged eurobench_nvidia_ros_reemc_madrob:latest
```

NOTE. Once the docker builds the image it is important to run the container and build the catkin workspace. The docker image also outputs the suggested command while building (green in the figure).

Build ROS Packages

As anticipated, once the docker container is executed it is mandatory to run the `catkin build` command to properly configure the ros packages. In order to do so execute the container and run the catkin build command:

```
$ sudo ./run_the_container.sh <ImageID>
(docker-container)$ cd /home/roseurobench/reemc_public_ws/
(docker-container)$ source /opt/ros/kinetic/setup.bash
(docker-container)$ catkin build -DCATKIN_ENABLE_TESTING=0
```

NOTE. The run outputs the container ID <ContainerID> to be used in order to execute the newly built image.

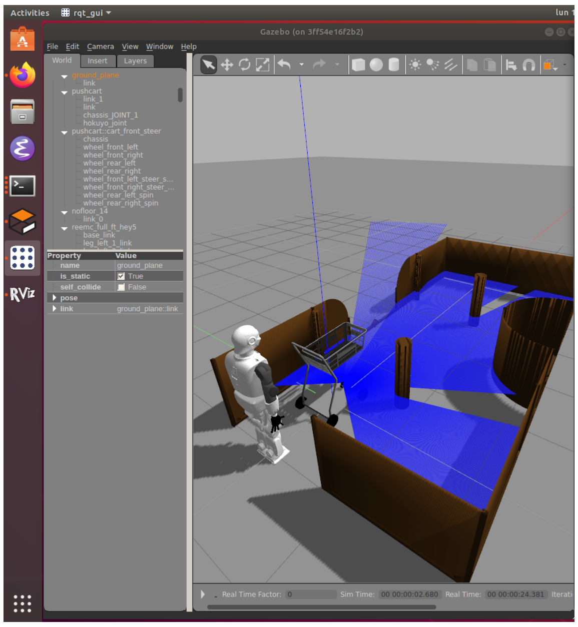
Installation Check

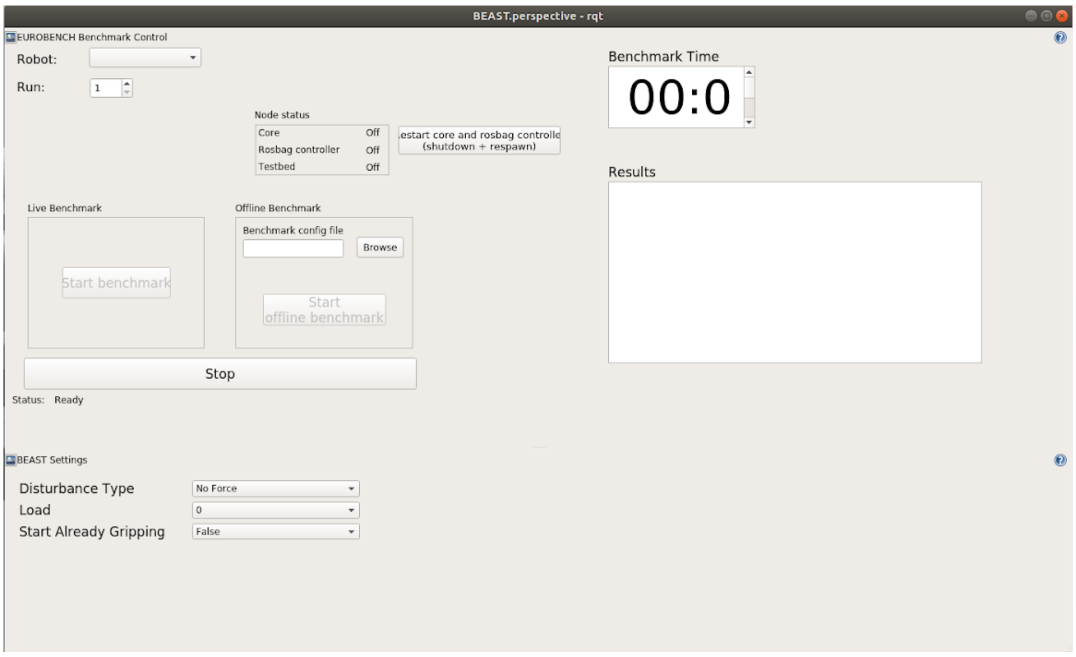
Check that everything is installed correctly by launching the simulator. To this end run the script that you find in the root of the repository by inserting the image ID printed out at the build phase. Once the ROS packages have been compiled you can open a different terminal and attach from it by using the <ContainerID>.

```
$ sudo docker exec -it <ContainerID> /bin/bash
(docker-container)$ source /home/roseurobench/reemc_public_ws/devel/setup.bash
(docker-container)$ QT_X11_NO_MITSHM=1 roslaunch eurobench_reemc_cart
reemc_cart.launch
```

The roslaunch command executes the simulation environment and shows the Reem-c robot facing a pushcart. If everything has been installed correctly this is what should be visualized.

NOTE. QT_X11_NO_MITSHM=1 is mandatory and tells QT to send the screen of the simulation, throughout the proper channels, outside the container.




BEAST.perspective - rqt

EUROBENCH Benchmark Control

Robot:

Run: 1

Node status

Core	Off
Rosbag controller	Off
Testbed	Off

estart core and rosbag controlle (shutdown + respawn)

Benchmark Time

00:0

Results

Live Benchmark

Start benchmark

Offline Benchmark

Benchmark config file

Browse

Start offline benchmark

Stop

Status: Ready

BEAST Settings

Disturbance Type	No Force
Load	0
Start Already Gripping	False

How To Run

How to Launch

The use of docker containers makes the use of the simulator safe and intuitive. In fact, once it has been properly installed, the simulator makes its execution run seemingless on any

machine. To properly launch a simulation of the benchmark we need to go through three steps. First, we need to launch the BEAST core nodes. Second, we need to launch the simulator node that takes care of setting up both the BEAST simulation middleware and the gazebo simulator with BEAST pushcart-plugin. Lastly, we need to launch a monitoring node that visualizes the sensory information coming from the simulator. Hence, to launch the BEAST core nodes open a terminal and gain access to the docker container previously installed.
If it is the first time and you need to create the container open a terminal and run

```
$ sudo ./run_the_container.sh <ImageID>
(docker-container)$ cd /home/roseurobench/reemc_public_ws/
(docker-container)$ source /opt/ros/kinetic/setup.bash
(docker-container)$ catkin build -DCATKIN_ENABLE_TESTING=0
(docker-container)$ roslaunch eurobench_benchmark_core beast_all.launch
```

Else, if a container of the BEAST simulator has already been created you can attach to the container from a different terminal and launch the BEAST core by using the following instructions

```
$ sudo docker exec -it <ContainerID> /bin/bash
(docker-container)$ roslaunch eurobench_benchmark_core beast_all.launch
```

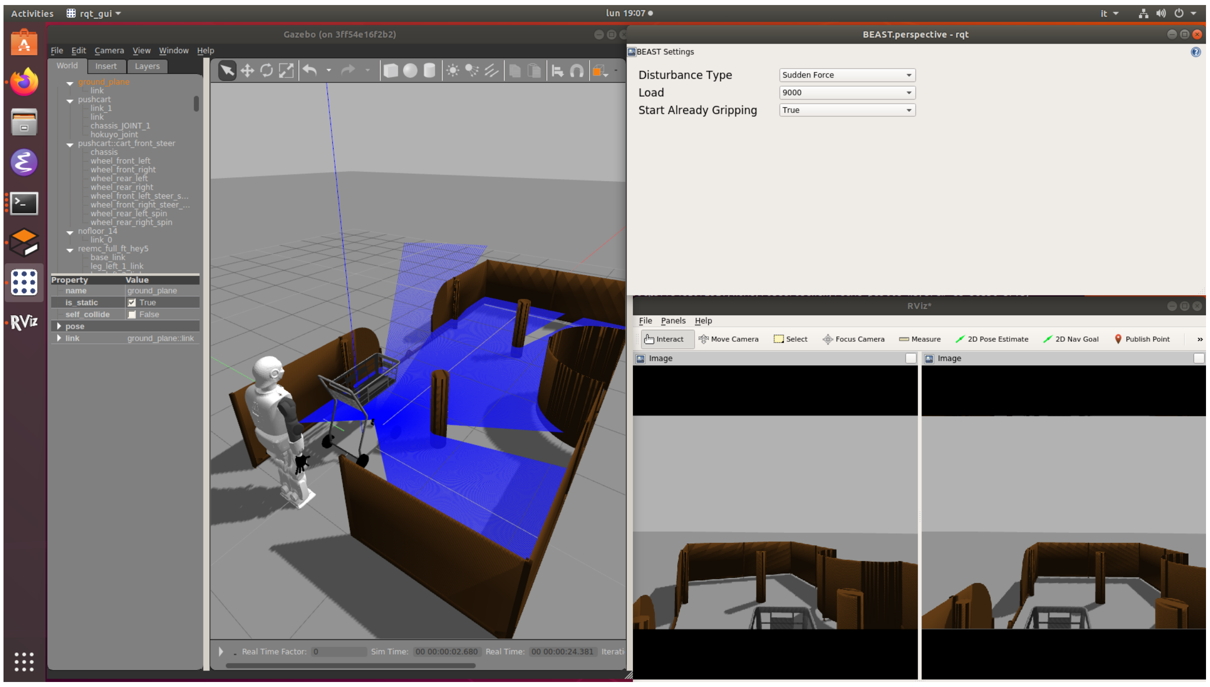
The second step launched the actual simulation. To this end, open a new terminal and attach to the same container. Then launch the simulation

```
$ sudo docker exec -it <ContainerID> /bin/bash
(docker-container)$ QT_X11_NO_MITSHM=1 rosrun beast_simulation_state_collector
beast_simulation_state_collector_node.py
```

Finally, to run the sensor GUI interface to monitor the robot camera stream and visualize the benchmark sensors, open a third terminal and run

```
$ sudo docker exec -it <ContainerID> /bin/bash
(docker-container)$ roslaunch benchmark_gui beast_sensors_gui.launch
```

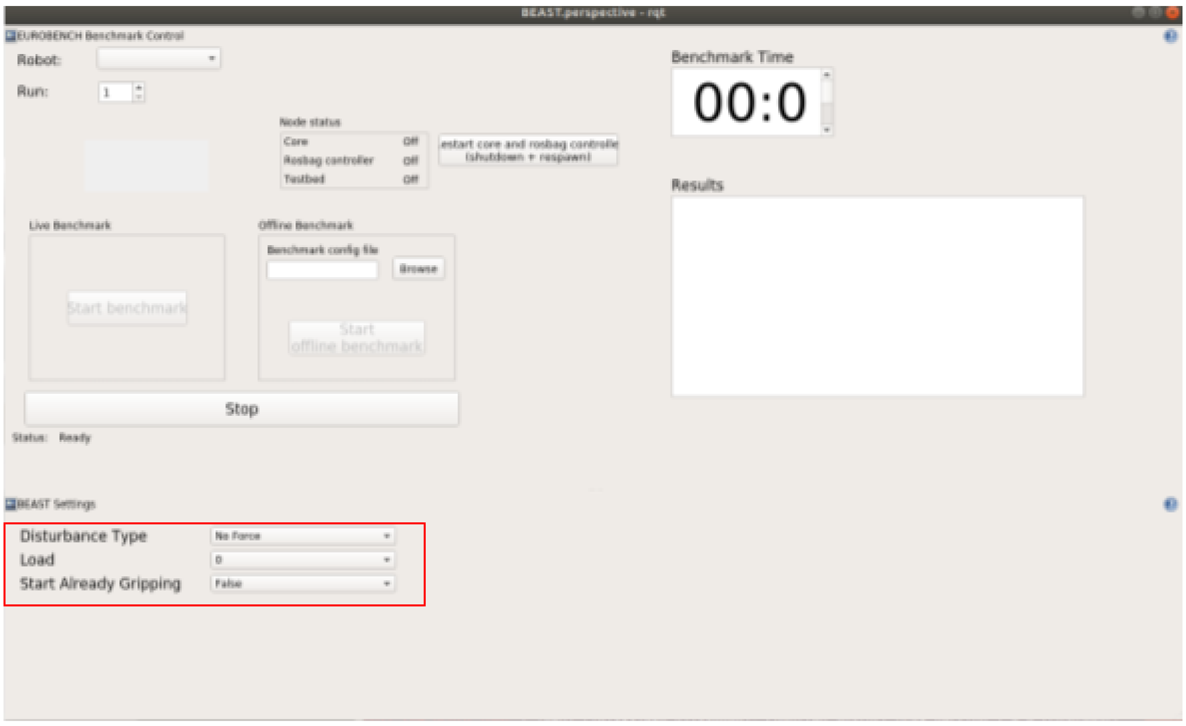
Once the procedure is complete both the BEAST official GUI and the Gazebo simulated Reem-C robot appear to screen and are ready to use. The figure below shows the simulation benchmark in idle.



Disturbance Type: Sudden Force
Load: 9000
Start Already Gripping: True

How to change Simulation Configuration

As for the real-robot benchmarks the simulations configuration can be changed through the BEAST-GUI. In fact, it is possible to reconfigure the pushcart wheel controller and update the LUT of the force torques profiles. In the next figure we highlight in red how to change the LUT force profiles.



Status: Ready

Disturbance Type: No Force
Load: 0
Start Already Gripping: False

Disturbance type

In the pushcart benchmark configuration bracket we can select from a list of disturbance force profiles, namely:

- No Force
- Sudden Force

Then we can choose the load and if the robot starts gripping.

It is important to note that this action does not stop nor restart the simulation and updates the force profiles online.
Note: In order to edit (or add) new force configurations, it is needed to edit and recompile the gazebo plugin *simple_cart_config.* In particular, the force profile lut values are located at "*eurobench_reemc_car/plugins/LUT.h"* in https://github.com/madrob-beast/eurobench_reemc_cart. LUTs are stored as vectors and are specified for each wheel.

Finally, it is important to understand that the simulation can begin only after the robot number is selected (in the upper left part of the GUI). This will be stored in the logging files.
The simulation can always be controlled using the Start/Stop button and once the benchmark is concluded results are stored in the docker container at **~/eurobench_output/** folder (or equivalently **/root/eurobench_output/**).
Note: the docker container has the **/root/** in the same folder of the **/home/** directory. Hence, even if the BEAST-core saves results in the home directory, the container saves them in the root due to the docker container file system.

Sensory Information Retrieval and Visualization

The simulation comes with a visualization node that allows for a visualization of the sensor observations, namely (1) the raw range sensor laser scan; (2) the interpreted distance data compliant with the BEAST message topics guideline template such as laser scan *min* filter, pushcart odometry and traversed checkpoints; (3) the pushcart handle contact forces; and (4) the robot camera images. For each of these sensor streams coming from the simulator node, the data flows on standard ROS topics. Topic names are listed below:

- Raw laser scan:

```
Data type: sensor_msgs/LaserScan
Header header
float32 angle_min
float32 angle_max
float32 angle_increment
float32 time_increment
float32 scan_time
float32 range_min
float32 range_max
float32[] ranges
float32[] intensities
```

- The distance sensor message is provided by the beast_msgs package within the BEAST core suite. The aforementioned simulated range sensors are thus processed to generate ROS topics that are compliant with the beast_msgs/Distance message and the BEAST guidelines. Post-processed information, as for the real-robot benchmark, are streamed on the following topics:

```
Data type: beast_msgs/ObstacleDistance
float32 timestamp
float32 distance  # [m]
```

- Preprocessed pushcart velocity published on /beast/Velocity which is computed by filtering raw data coming from the /odom topic. The topic publishes linear and angular velocity of the pushcart with respect to the testbed origin reference frame. The x, y, theta values follow the amcl ROS package convention:

```
Data type: beast_msgs/Velocity
float32 timestamp
float32 x  # [m/s]
float32 y  # [m/s]
float32 theta  # [rad/s]
```

- Preprocessed pushcart pose published on /beast/Pose which is computed by filtering raw data coming from the tf frame /base_link. The topic publishes Position and orientation of the pushcart with respect to the testbed origin reference frame. The x, y, theta values follow the amcl ROS package convention

```
Data type: beast_msgs/Pose
float32 timestamp
float32 x  # [m]
float32 y  # [m]
float32 theta  # [rad]
```

- Preprocessed pushcart velocity published on /beast/handle/force :

```
Data type: beast_msgs/ForceOnHandle
float32 timestamp
float32 force  # [gr]
```

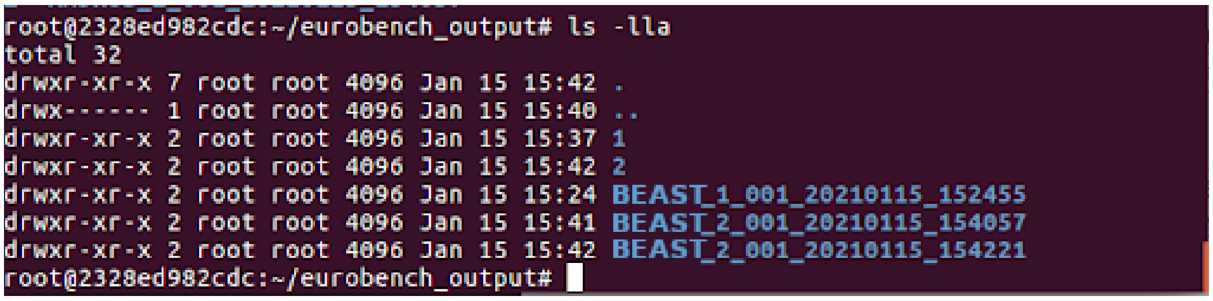
- Image streaming from left and right cameras:

```
Data type: sensor_msgs/CompressedImage
/stereo/left/image/compressed
/stereo/right/image/compressed
```

The sensory data can be visualized with the eurobench BEAST_sensor_perspective. By using this tool it is possible to have realtime camera streams and sensor data plots. The two camera plots can be chosen in the upper drop down menus of the GUI. All the remaining sensory data flows can be added to the graphical interface by choosing the topic in one of the two selector and by pressing the plus sign. Regardless of the sensor_perspective tool, the sensory data stream can be always visualized through the ROS visualization tool Rviz.

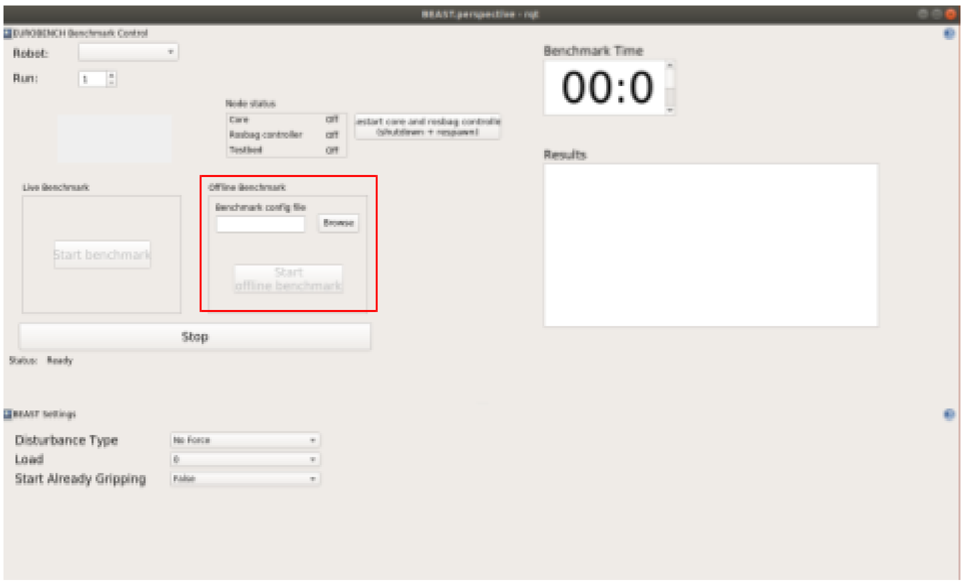
How to Replay Results

In order to replay a particular run of the benchmark, locate the desired output in **~/eurobench_output/**. The figure below shows an example of the content in the output directory. Here are listed three different runs of the benchmark. The single digit folder <ROBOT-NUM> contains a .txt file that stores information about the robot used for the experiment and the benchmark configurations parameters and statistics. The GUI allows the selection of two types or robots, hence there can be a maximum of two folders labeled with a digit number. Conversely, the folder named BEAST_<ROBOT-NUM>_<EXP-ID> contains information related to each individual run of the benchmark. In each folder there is a .yaml needed to index and replay the benchmark, a ROS bags file with all the topic sensory data, and two .csv files storing the events occurred during the simulation, and the record of the applied forces.



```
root@2328ed982cdc:~/eurobench_output# ls -lla
total 32
drwxr-xr-x 7 root root 4096 Jan 15 15:42 .
drwx------ 1 root root 4096 Jan 15 15:40 ..
drwxr-xr-x 2 root root 4096 Jan 15 15:37 1
drwxr-xr-x 2 root root 4096 Jan 15 15:42 2
drwxr-xr-x 2 root root 4096 Jan 15 15:24 BEAST_1_001_20210115_152455
drwxr-xr-x 2 root root 4096 Jan 15 15:41 BEAST_2_001_20210115_154057
drwxr-xr-x 2 root root 4096 Jan 15 15:42 BEAST_2_001_20210115_154221
root@2328ed982cdc:~/eurobench_output#
```

The .yaml file inside the folder BEAST_<ROBOT-NUM>_<EXP-ID> can be used to replay offline simulation experiments, as in the case of real-robot benchmark execution. To this end, it is possible to input the full path to the .yaml file of a particular experiment in the *Offline benchmark* section of the beast.perspective.GUI and then press the *Start offline benchmark* button. This is highlighted in the image below.



Robot:

Run: 1

Node status

Core	off
Rosbag controller	off
Testbed	off

Status: Ready

Disturbance Type	No Force
Load	0
Start Already Gripping	False